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Spent Fuel and Waste Science and Technology (SFWST)

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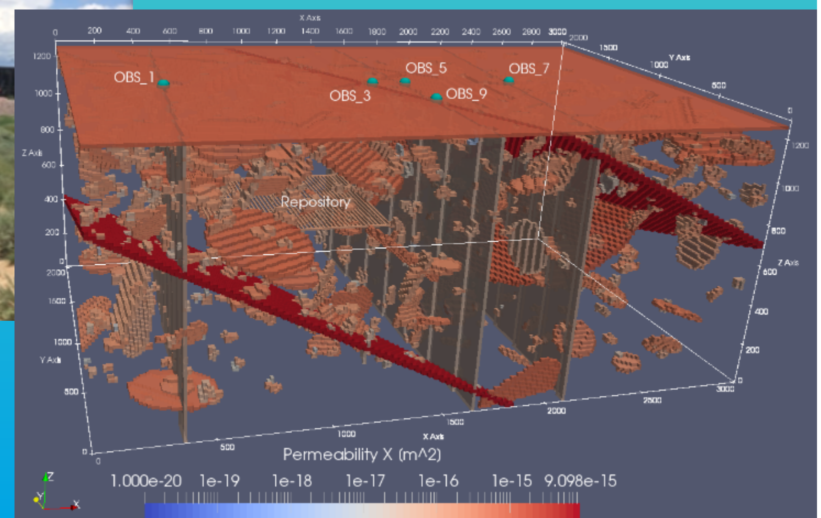

Reactivity Analyses

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Nuclear Waste Technical Review Board
Summer 2020 Board Meeting
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Online Virtual Meeting

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This is a technical presentation that does not take into account the contractual limitations or obligations under the Standard Contract for Disposal of Spent Nuclear Fuel and/or High-Level Radioactive Waste (Standard Contract) (10 CFR Part 961). For example, under the provisions of the Standard Contract, spent nuclear fuel in multi-assembly canisters is not an acceptable waste form, absent a mutually agreed to contract amendment.

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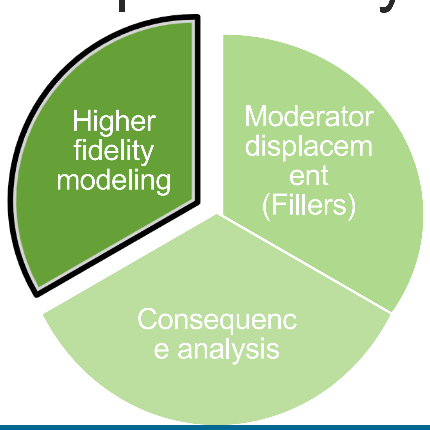
This presentation reflects technical work which could support future decision making by DOE. No inferences should be drawn from this presentation regarding future actions by DOE, which are limited both by the terms of the Standard Contract and Congressional appropriations for the Department to fulfill its obligations under the Nuclear Waste Policy Act including licensing and construction of a spent nuclear fuel repository.

Criticality analysis of DPCs is being performed to identify DPCs with criticality potential in a repository

- Majority of the spent nuclear fuel (SNF) is being stored in dual-purpose (storage and transportation) canisters (DPCs)
  - DPCs are not designed or loaded with disposal considerations
- Aluminum-based neutron absorbers typically used in DPCs are not expected to provide criticality control during a repository performance period (e.g., 10,000 years or more), specially in aqueous environment
  - Design-basis analysis (without basket neutron absorber credit) would incorrectly show that all loaded DPCs can achieve criticality when flooded in a repository
- As-loaded criticality analysis is being used to identify DPCs that can potentially achieve criticality in a repository when flooded



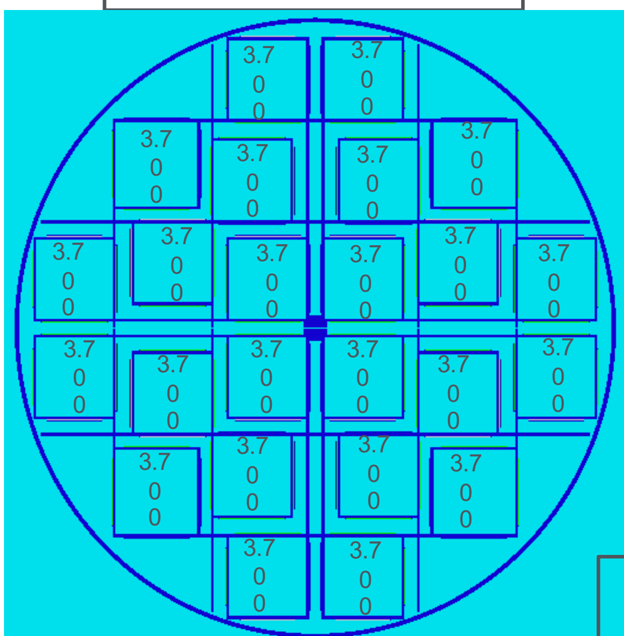
Things to remember

- Effective neutron multiplication factor (k_{eff}) = 1 means a system is critical
- $k_{eff} < 1$ means subcritical
- $k_{eff} > 1$ means supercritical
- SNF in DPCs need water or moderator to achieve criticality
- No water no criticality

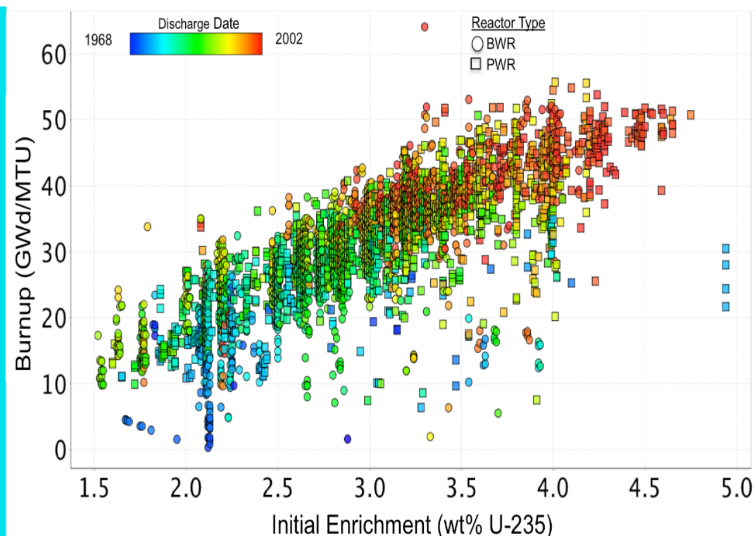
As-loaded criticality analysis (fully flooded) can be used to quantify uncredited margin

- Current design-basis approach uses bounding fuel characteristics (e.g., fuel type, initial enrichment, and discharge burnup) for SNF storage and transportation systems certification process
- In practice, discharge SNF assemblies available for loading are diverse (e.g., wide variation in SNF assembly burnup values)

Design-basis k_{eff} = 0.90

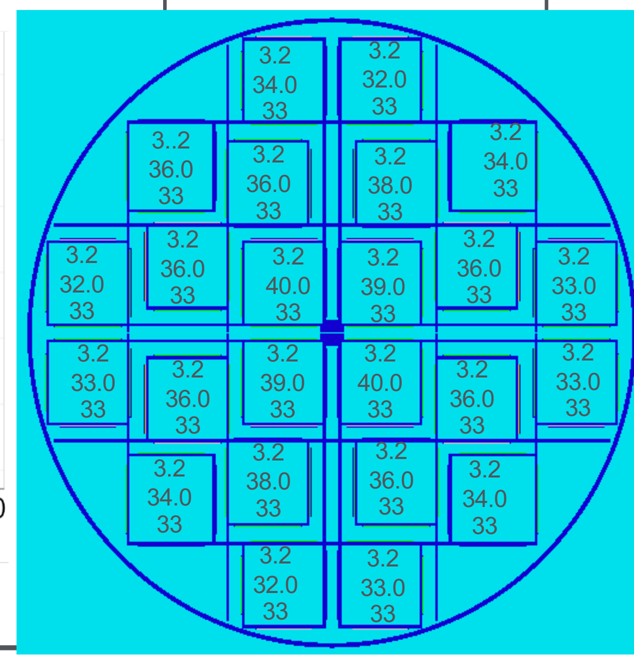


Discharged inventory



X	Assembly average initial enrichment (wt %)
Y	Assembly average burnup (GWd/MTU)
Z	Cooling (years)

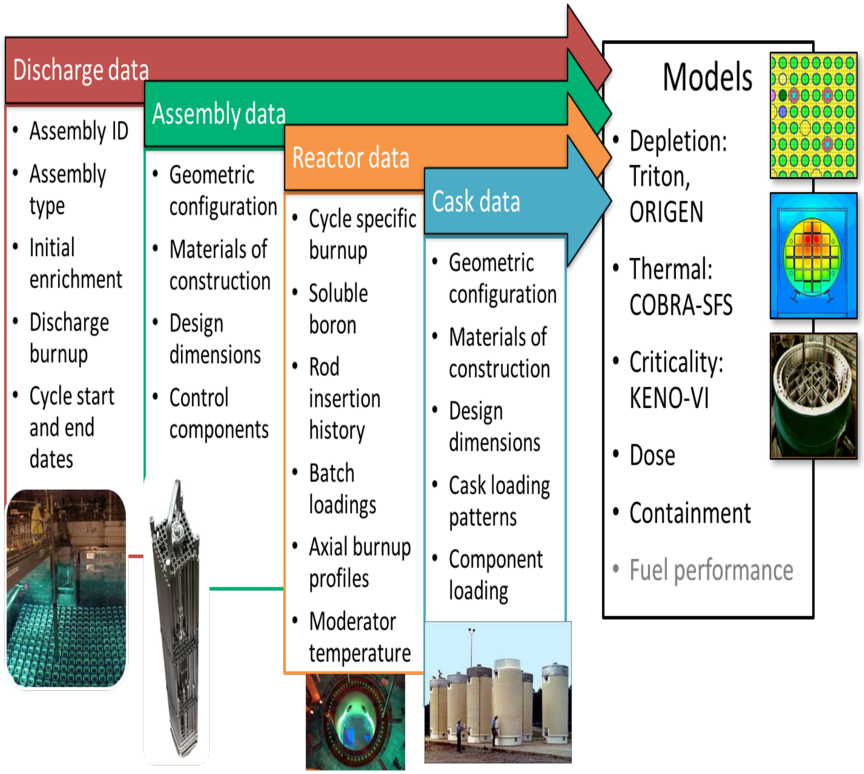
As-loaded k_{eff} = 0.66



Uncredited margin = 0.90-0.66 = 0.24 Δk_{eff}

UNF-ST&DARDS has been developed to perform as-loaded analyses

- Used Nuclear Fuel- Storage, Transportation & Disposal Analysis Resource and Data System (UNF-ST&DARDS) streamlines various waste management related analyses
- UNF-ST&DARDS provides a comprehensive database and integrated analysis tools
- Data relations facilitate analysis automation
  - Minimum user interaction reduces potential for human error
- UNF-ST&DARDS currently uses SCALE for criticality analysis



As-loaded analysis is performed in two steps – depletion/decay and criticality

- As-loaded criticality analysis with full (actinides and fission products) burnup credit requires time dependent isotopic number densities – depletion and decay calculation
  - SCALE TRITON two-dimensional depletion sequence and ORIGEN are used for isotopic number densities
- Time dependent isotopic composition of the SNF is used to determine canister k_{eff} – criticality calculation
  - KENO-VI is used for criticality calculation with continuous energy ENDF/B-VII.1 cross section library

UNF-ST&DARDS as-loaded criticality analysis uses limiting burnup profiles based on burnup range

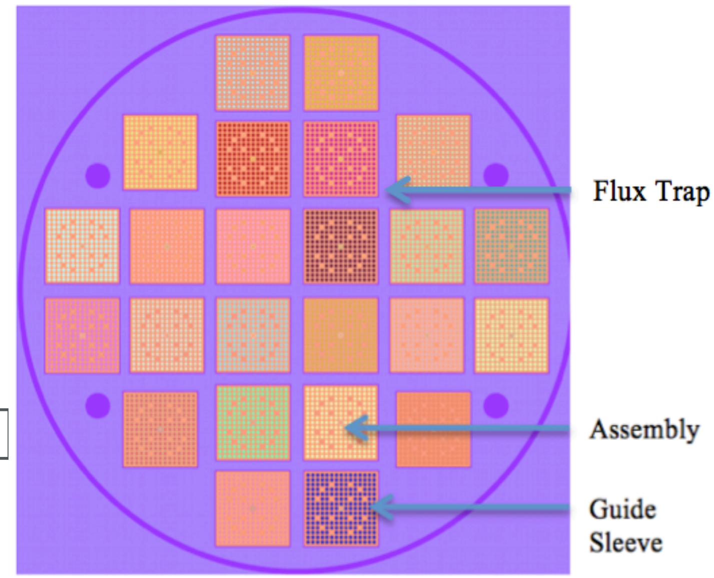
- Conservative depletion modeling techniques used
- PWR
  - High soluble boron concentration, low moderator density, burnable absorber throughout life of assembly in reactor
  - Bounding PWR burnup profiles from NUREG/CR-6801 “Recommendations for Addressing Axial Burnup in PWR Burnup Credit Analyses”
- BWR
  - Blade insertion throughout life, relatively high void fraction
  - Limiting BWR burnup profiles have been selected from Commercial Reactor Criticality (CRC) Data

UNF-ST&DARDS as-loaded disposal analysis model includes postulated degradation

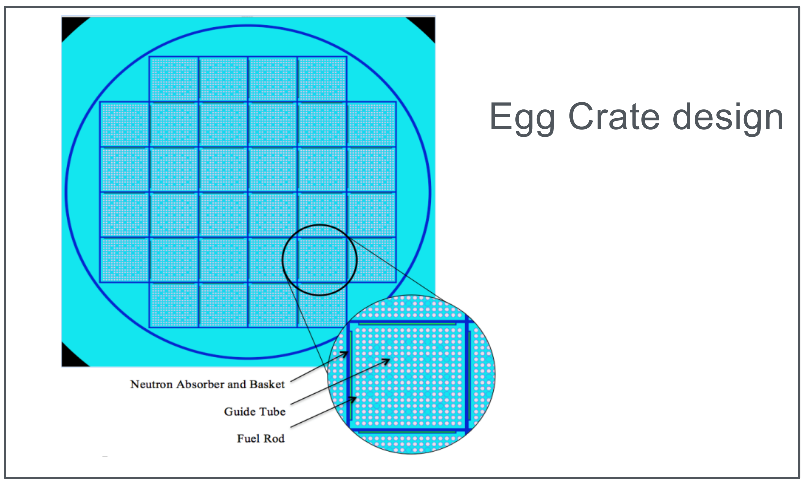
Two simplified, conservative degradation scenarios are used for disposal analysis

Loss of neutron absorber: In this scenario, there is a total loss of basket neutron absorber components from unspecified degradation and material transport processes with replacement by groundwater

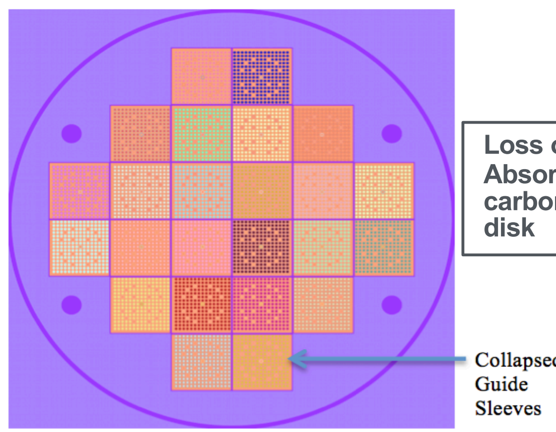
Basket degradation: Loss of carbon steel components and neutron absorber panels



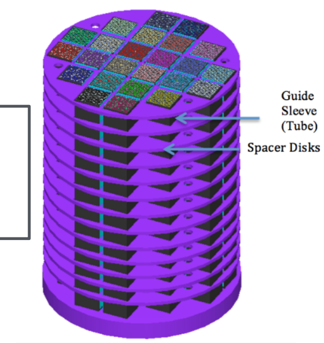
Loss of neutron absorber



MPC-32 canister Storage/transportation model



Loss of neutron Absorber + carbon steel disk



Canister differentiator: Flux trap vs. egg crate designs

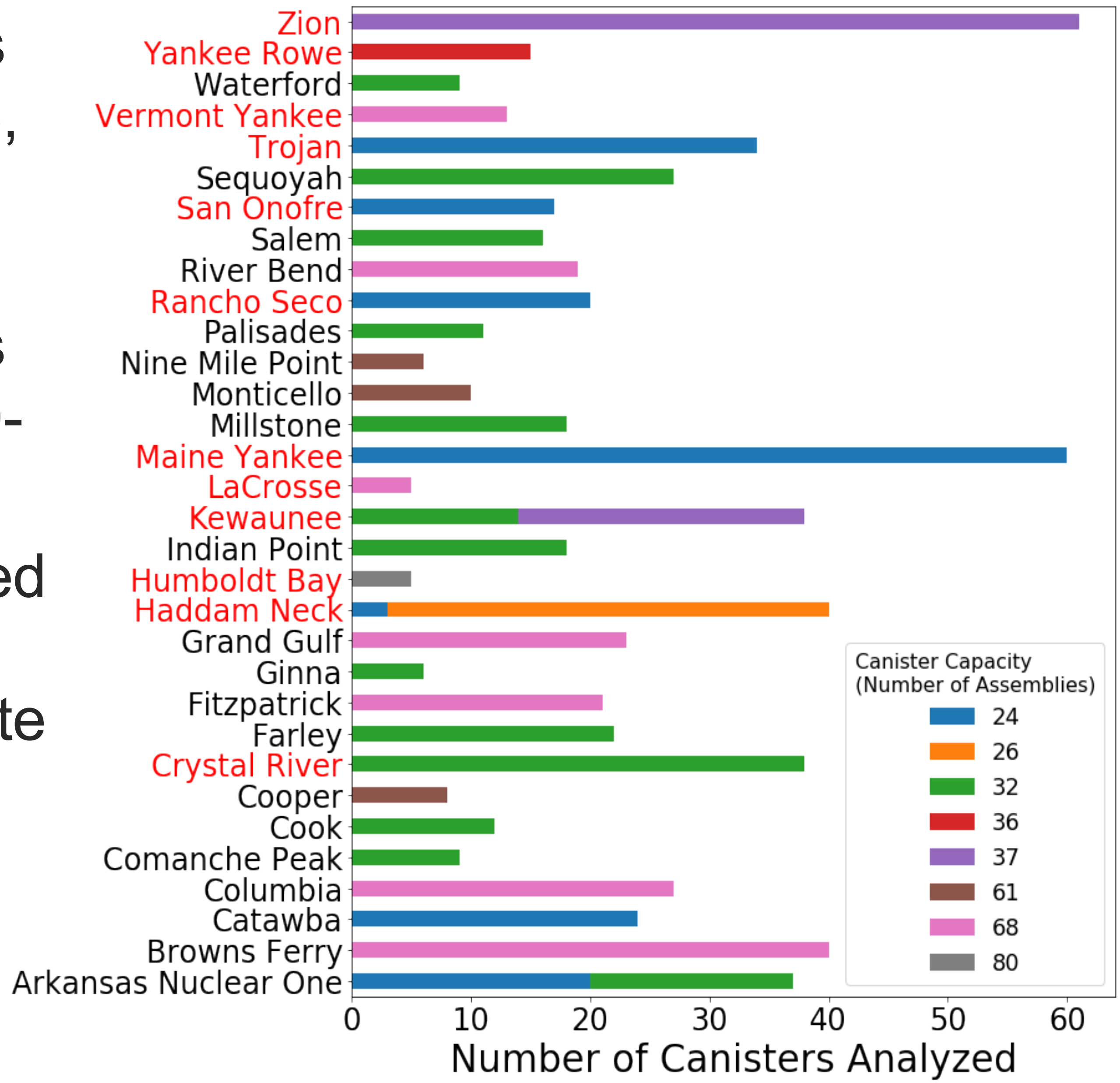
Models are verified by comparing with the safety analysis report

- UNF-ST&DARDS storage/transportation criticality models are run with design-basis fuel characteristics from safety analysis report and results are compared with safety analysis report to perform model verification and validation
  - Verified storage/transportation criticality models are modified to incorporate disposal scenarios

Canister Name	Flux Trap?	^{10}B Areal Density In Neutron Absorber (g/cm^2)	Canister Construction	Contains Carbon Steel?	Reference k_{eff}	Calculated Reference k_{eff} (UNF-ST&DARDS)
TSC-24	Yes	0.0250	Tube and disk	No	0.9192	0.9187 ± 0.00017
TSC-37	No	0.0360	Egg crate	Yes	0.9189	0.9193 ± 0.00047
CY-MPC 26	Yes	0.0200	Tube and disk	No	0.9064	0.8991 ± 0.00029
CY-MPC 24	Yes	0.0200	Tube and disk	No	0.9197	0.9132 ± 0.00024
Yankee-MPC	Yes	0.0100	Tube and disk	No	0.8761	0.8767 ± 0.00045
MPC-24E/EF	Yes	0.0250	Egg crate	No	0.9187	0.9006 ± 0.00026
MPC-24	Yes	0.0267	Egg crate	No	0.9325	0.9302 ± 0.00022
MPC-32	No	0.0372	Egg crate	No	0.9123	0.9076 ± 0.00018
FO/FC-DSC	Yes	0.0216	Tube and disk	Yes	0.9316	0.9316 ± 0.00026
MPC-LACBWR	Yes	0.0200	Tube and disk	No	0.8420	0.8451 ± 0.00044
MPC-HB	No	0.0100	Egg crate	No	0.8318	0.8331 ± 0.00034
MPC-68	No	0.0372	Egg crate	No	0.9273	0.9274 ± 0.00026

As-loaded criticality analysis has been performed for 708 already loaded canisters at 32 sites

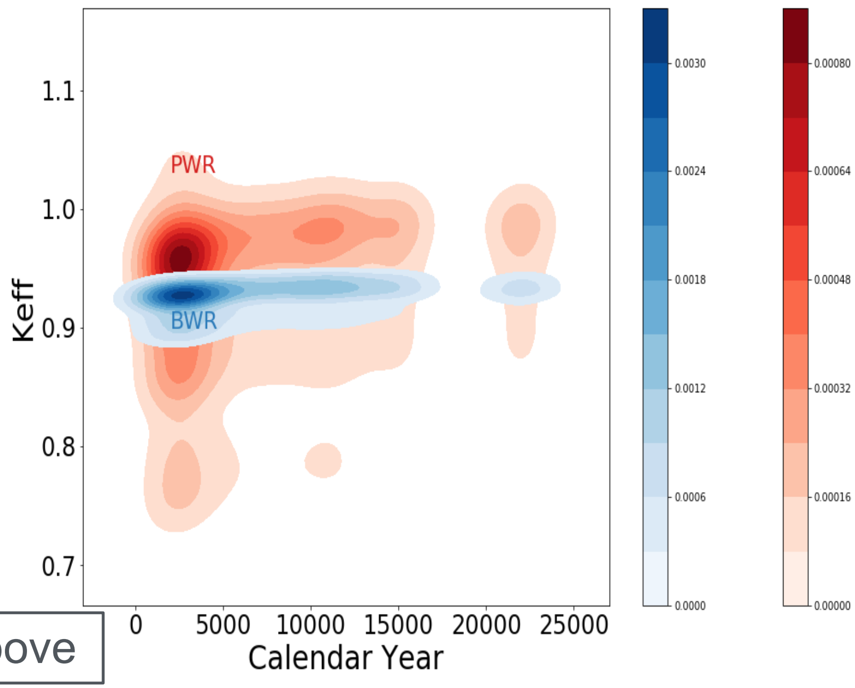
- Analyzed PWR DPCs include 24, 26, 32, 36, and 37-assembly capacity
- Analyzed BWR DPCs include 61, 68 and 80-assembly capacity
- Calculations performed for each DPC from canister in-service date to year 22,000



68% of analyzed DPCs are below the representative subcritical limit with as-loaded analysis (fresh water)

- A representative subcritical limit (considered as 0.98 k_{eff}) is used for this analysis

Description (Analysis Dates: 2020-22000)	Value
Total DPCs analyzed	708
Total DPCs below subcritical limit with loss of neutron absorber (design-basis loading)	0 (0%)
Total DPCs below subcritical limit with loss of neutron absorber (as-loaded)	556 (~79%)
Total DPCs below subcritical limit with loss of neutron absorber and carbon steel structures (as-loaded)	483 (~68%)

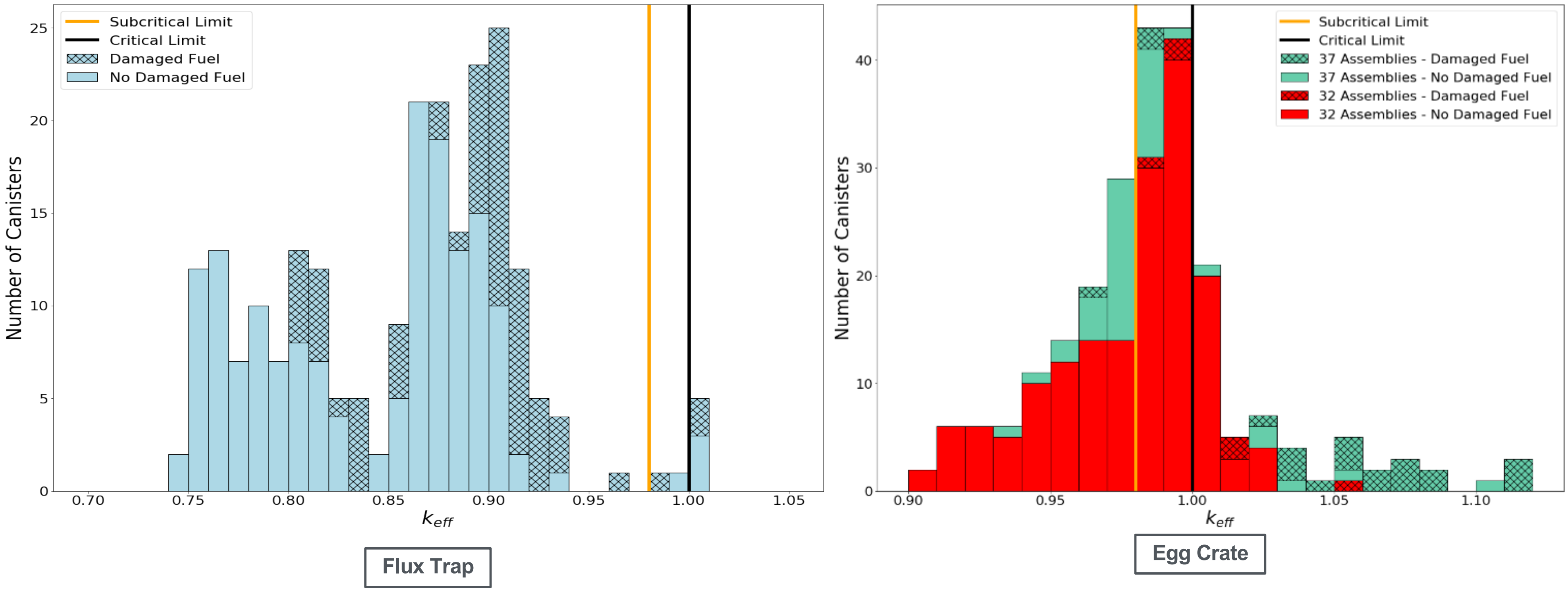


* Misload is not considered in the statistics presented above

For PWRs subcritical margin demonstrated for flux trap canisters but challenging for egg crate designs

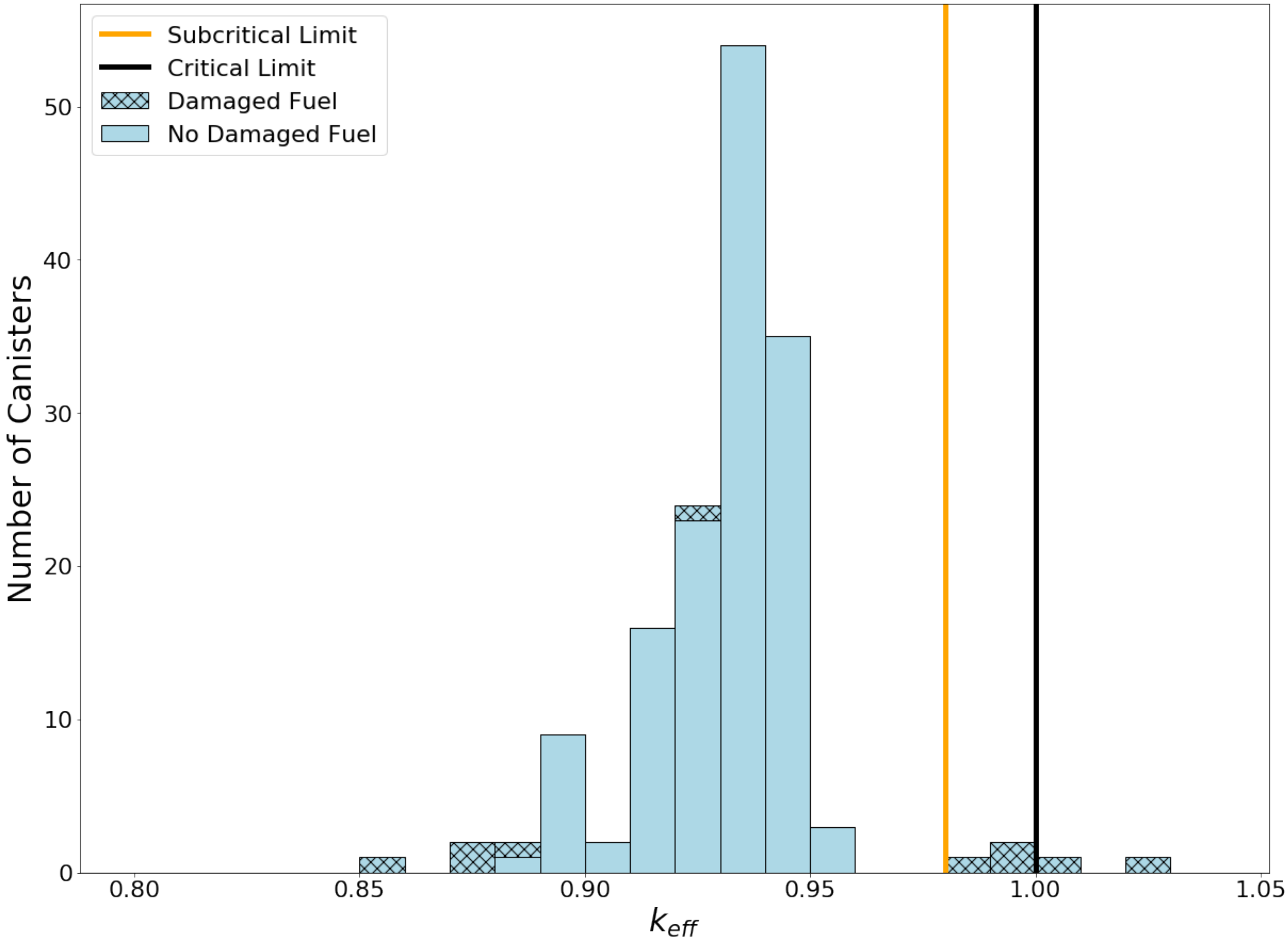
- **Criticality analysis is performed with safety analysis report damaged fuel assumption**
  - **Typically fresh fuel with optimum fuel pin lattice spacing**
  - **This assumption can be improved with better data**

Loss of neutron absorber disposal scenario



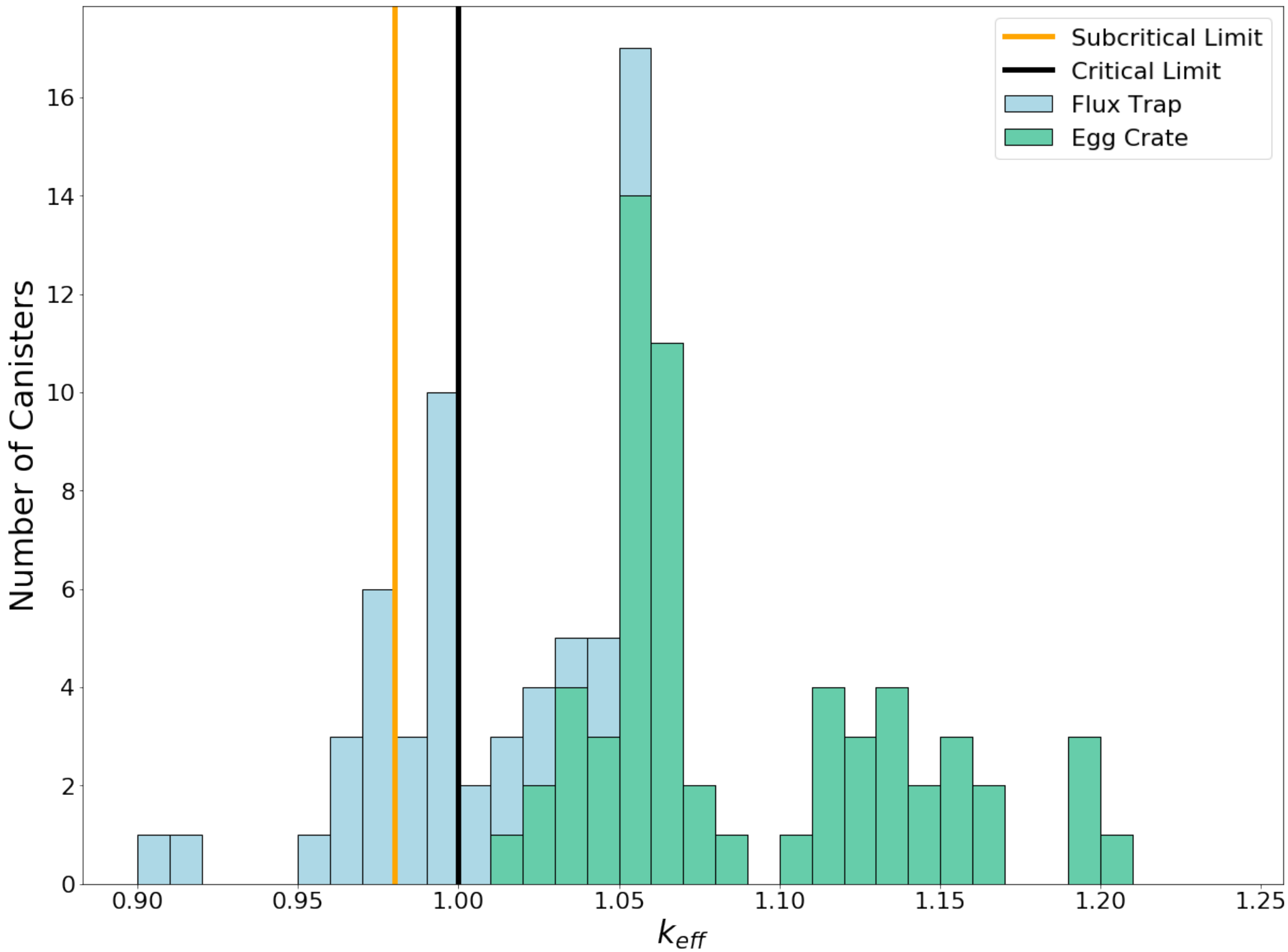
The DPCs are always modeled with disposal scenarios (e.g., no basket neutron absorber), damaged fuel is only modeled if a DPC is loaded with damaged fuel assemblies.

BWR loss-of-neutron-absorber results show margin for the majority of canisters



Loss of neutron absorber disposal scenario

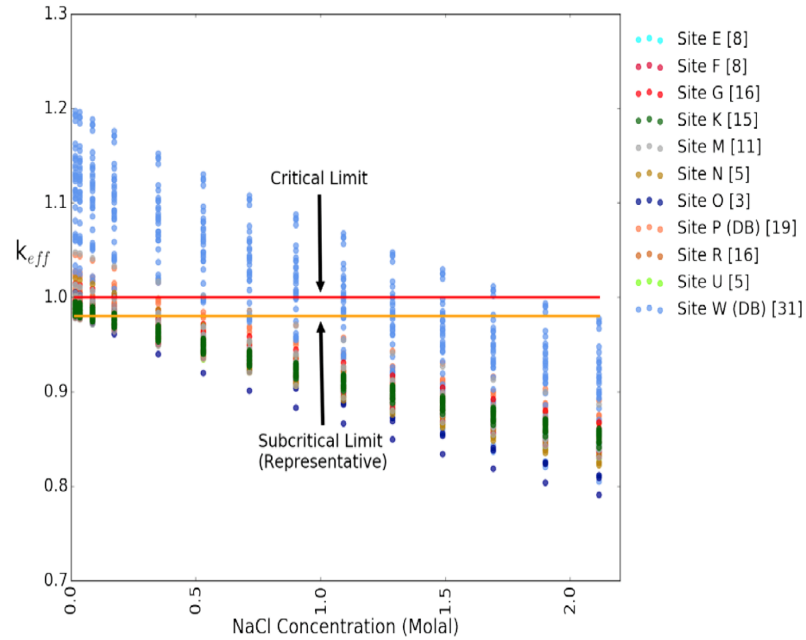
Degraded basket configuration challenging for margin demonstration



Basket degradation disposal scenario

Chlorine (Cl), if present in the geological media can provide noticeable reactivity reduction

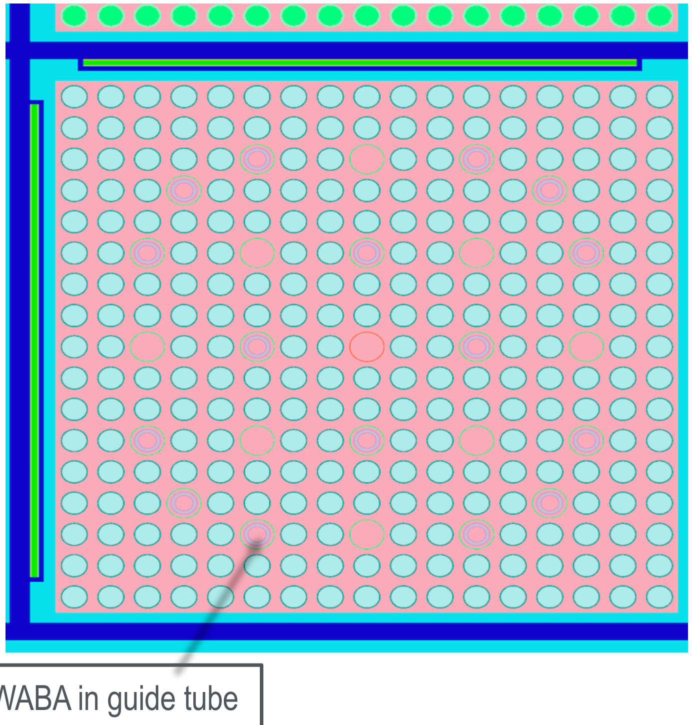
- Canisters that are above subcritical limit with as-loaded analysis are analyzed with Cl (NaCl)
- In addition to salt repository, Cl is available (in moderate quantity) in clay, granite, and crystalline rock
- Literature reviews show that Lithium and Boron may also be available in small quantity in some geological media
  - Can provide substantial reactivity reduction
  - Other commonly available dissolved aqueous species may not yield a significant neutron absorption effect



k_{eff} vs NaCl concentration for the Loss-of-Neutron-Absorber Case (Except for Site P and W that were Analyzed with Degraded Baskets) for canisters with k_{eff} above 0.98 based on actual loading

Presence of non-fuel components in DPCs may provide some reactivity reduction

- Different types of components are currently stored in the guide tubes of the PWR SNF assemblies
  - Burnable poison rod assemblies (BPRAs), wet annular burnable absorbers (WABAs), and control rod assemblies (CRAs)
- Limited studies were performed by taking water displacement only non-fuel component credit
  - WABA design was considered (provides least amount of water displacement)
  - 16 WABA rods/fingers were modeled, irrespective of actual number of rods
  - Non-fuel component model will be extended to all PWR DPCs



DPC ID	K_{eff} without component @ year 9999	K_{eff} with component @ year 9999	Δk
MPC-005	1.0048	0.9987	0.0061
MPC-006	0.9808	0.9747	0.0061
MPC-0109	0.9705	0.9642	0.0063
MPC-0110	0.9587	0.9531	0.0056
MPC-0177	0.9981	0.9925	0.0056
MPC-068	0.9874	0.9818	0.0056
MPC-070	0.9786	0.9728	0.0058

A misload analysis methodology has been developed supporting as-loaded criticality analysis

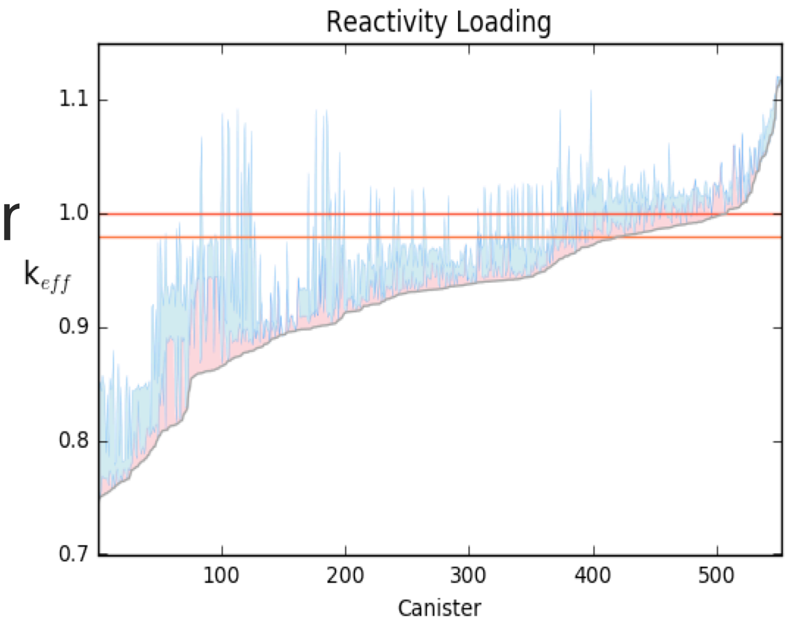
- Misload analysis methodology is developed to support direct disposal of loaded canisters using as-loaded analysis
- Nuclear Regulatory Commission Interim Staff Guidance (ISG-8 rev. 3) states:
  - "Misload analyses may be performed in lieu of a burnup measurement. A misload analysis should address potential events involving the placement of assemblies into a SNF storage or transportation system that do not meet the proposed loading criteria."
- Burnup measurement before loading of assemblies in a dry cask is not typically practiced in the United States

Misload is either selection of wrong set of assemblies from the pool or placing assemblies at unintended locations inside a cask

- NUREG-6998 mentions two different types of misloads
  1. The right assembly is selected but placed in the wrong position, and
  2. The wrong assembly is selected but placed in the intended position
     a) misloading of a single severely underburned assembly (ISG 8, Rev 3) in most reactive position
     b) misloading of multiple moderately underburned assemblies (ISG 8, Rev 3) in most reactive positions
- In a direct disposal scenario type 1 (placing assemblies in the wrong position inside the cask) is more likely to remain undetected as type 2 misload (selection of wrong assemblies) should be discovered during subsequent canister loadings
  - Assuming disposal from shutdown sites

Correct inventory in the wrong configuration (realistic scenario)-would not significantly increase the number of canisters above subcritical limit

- The most reactive available assemblies are determined by calculating the reactivity of each individual fuel assembly available in the reactors pool at the date of loading the canister
- To determine the most reactive position in the canister a regular criticality calculation is performed to determine the fission density in each position
- This analysis method has been automated and implemented in UNF-ST&DARDS

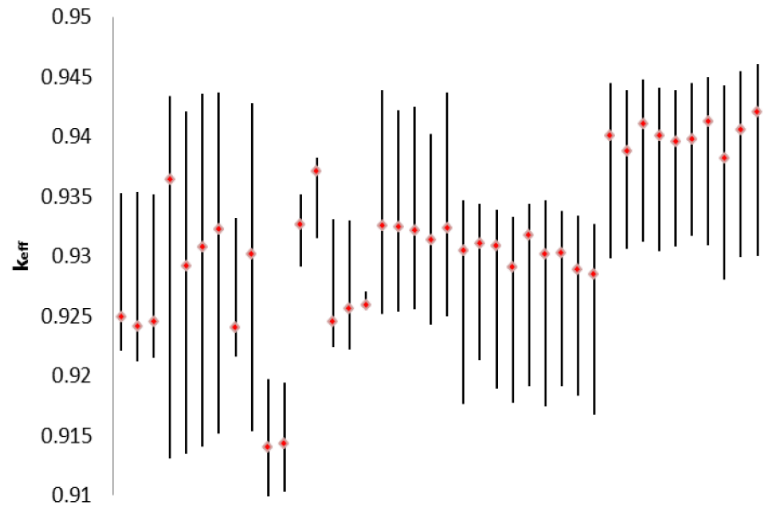


Misload Impact on k_{eff} from the 2 Different Misload Cases: Correct Inventory is Placed in the Most Reactive Configuration (Pink Fill), and the Most Reactive Assemblies Are Removed from the Pool and Placed in the Most Reactive Position in the DPC (Blue Fill)

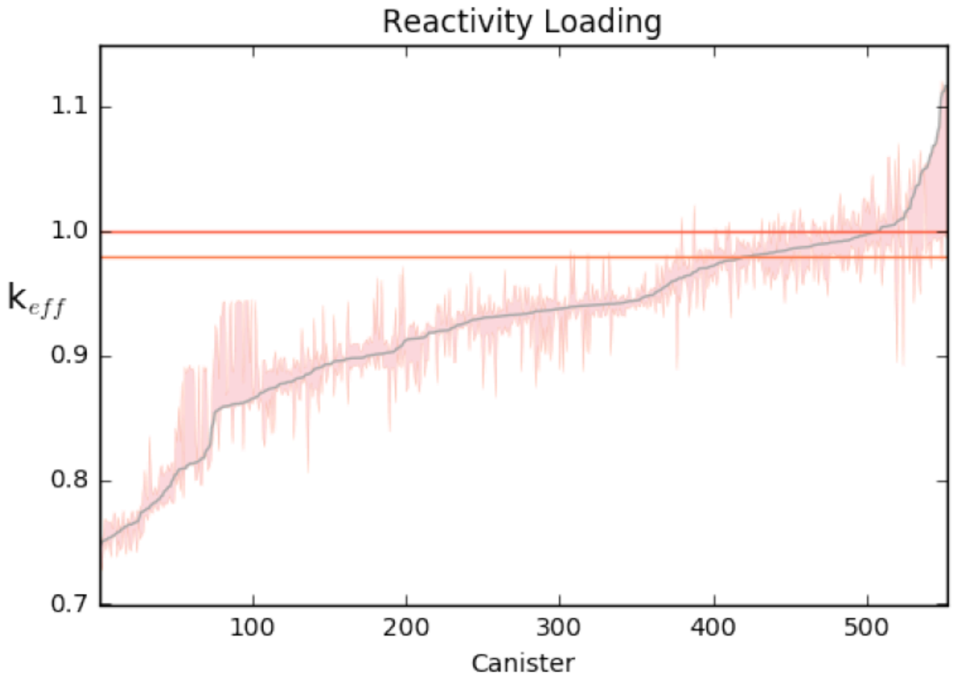
The misload approach is deterministic such that all the canisters are assumed to be misloaded

loading of DPCs can be optimized to reduce criticality potential in a disposal time frame

- Given canister inventory (list of assemblies) and a canister type, UNF-ST&DARDS can provide least reactive loading map (configuration)
- Current loading strategy
  - Reduce dose (low reactivity)
  - Reduce peak cladding temperature (high reactivity)



Red markers indicate the reactivity of the loaded canisters, and black lines are the range between optimized and worst possible loading using the same canister inventory.

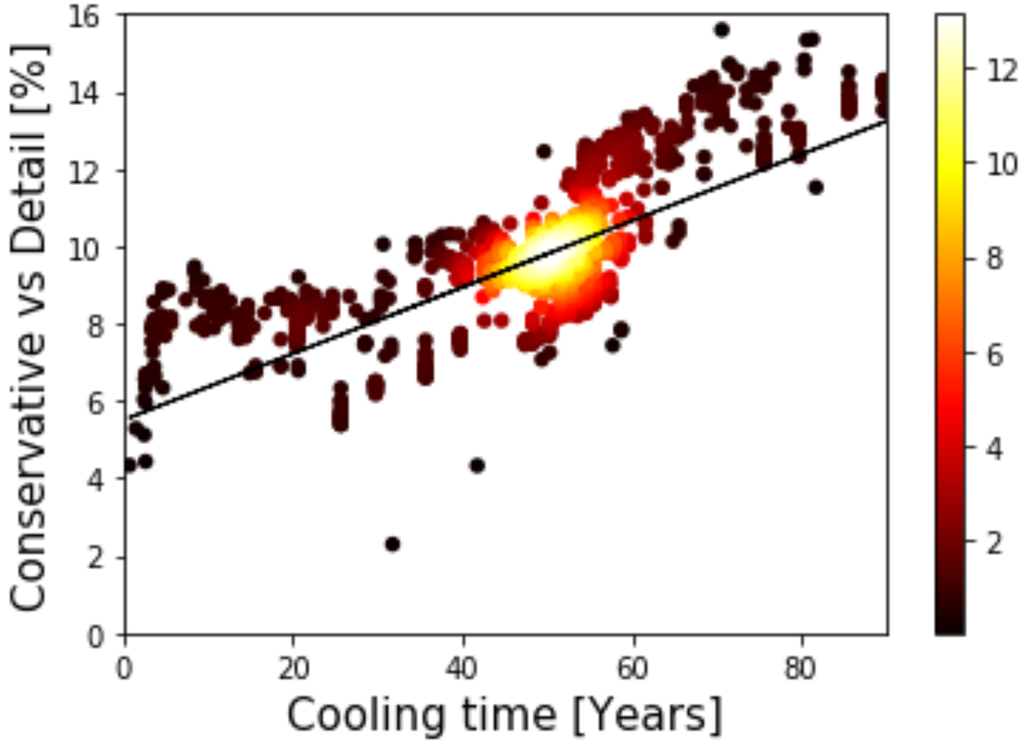


The reactivity of 556 canisters, as well as a band spanning from the least reactive to most reactive configuration. Note: **Most of the analyzed canisters with a k_{eff} above 1 have been loaded in a very reactive configuration and could have been loaded with k_{eff} between 1 and 0.98 using the same inventory with the assumed degradation scenario**

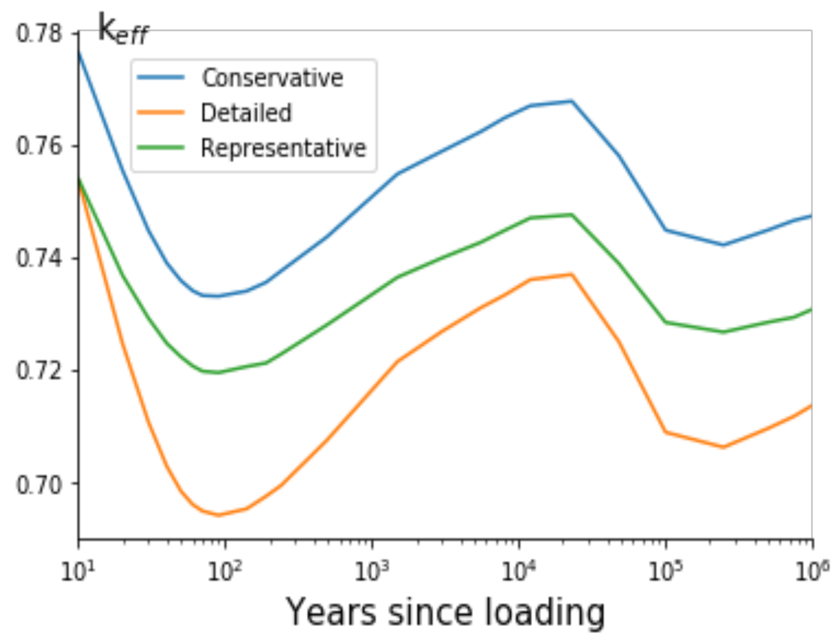
Detailed fuel and operational data are being used to validate UNF-ST&DARDS as-loaded approach

- A realistic set of validated as-loaded analysis parameters is needed as it is not practical to analyze every SNF assembly using detailed data
- Two approaches:
  - SCALE lattice physics code Polaris for rapidly generating pin-specific and average discharged isotopics for each node by modeling various reactor state points
  - Direct use of discharged isotopics from a core simulator that avoids any lattice physics analysis and provides a direct integration of UNF-ST&DARDS with core simulators for SNF management and analysis
- Objectives:
  - Identify excessive margin within the current approach for further improvement
  - Identify any non-conservatism within the current approach that must be corrected

Initial analysis results show UNF-ST&DARDS current as-loaded approach retains some margin



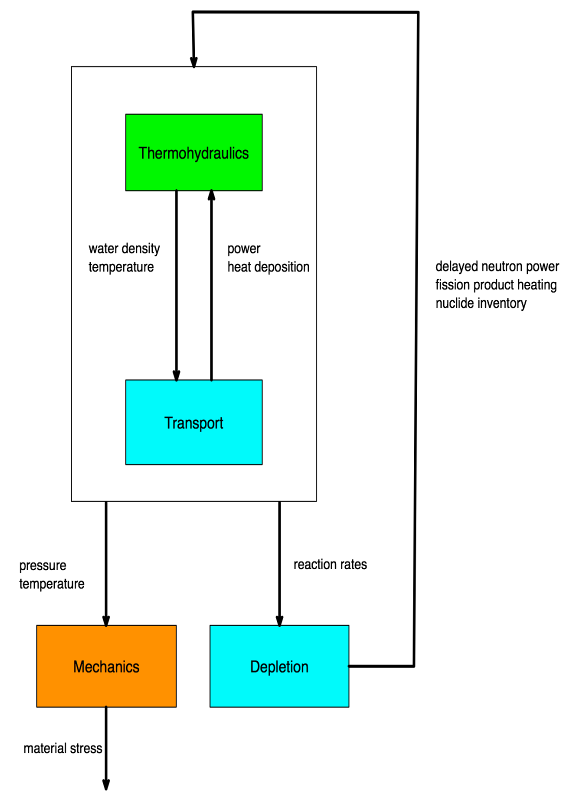
Preliminary percentage difference in decay heat between conservative (current UNF-ST&DARDS) and detail approaches. The color shows the density of analyzed assemblies



k_{eff} over time for a small disposal canister using conservative, representative, and detailed analysis approaches

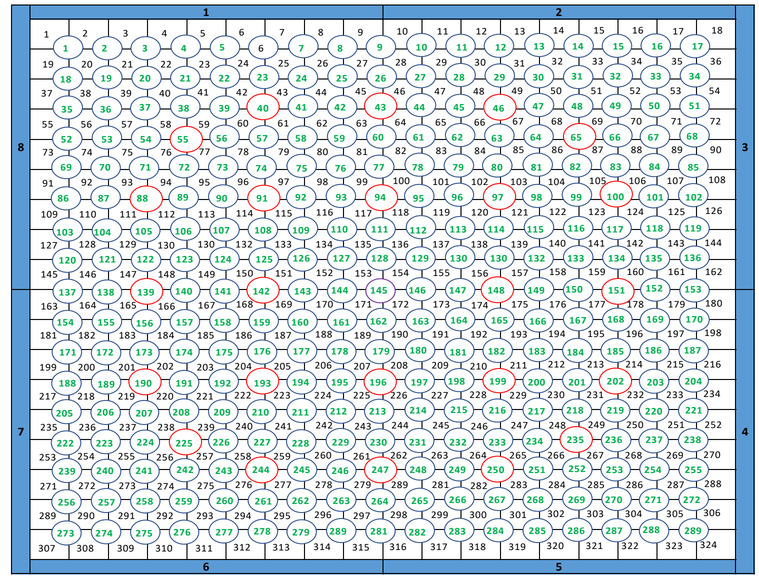
A multiphysics criticality consequence modeling tool is under development to simulate DPC criticality

- Couple various physics codes for Dual Purpose Canister modeling
  - **Terrenus** (multiphysics driver)
  - Radiation transport **(Shift)**
  - Nuclide depletion **(ORIGEN)**
  - Thermohydraulics **(COBRA-SFS)**
  - Mechanics **(TBD)**
- Demonstrate coupled capability on critical cask configurations

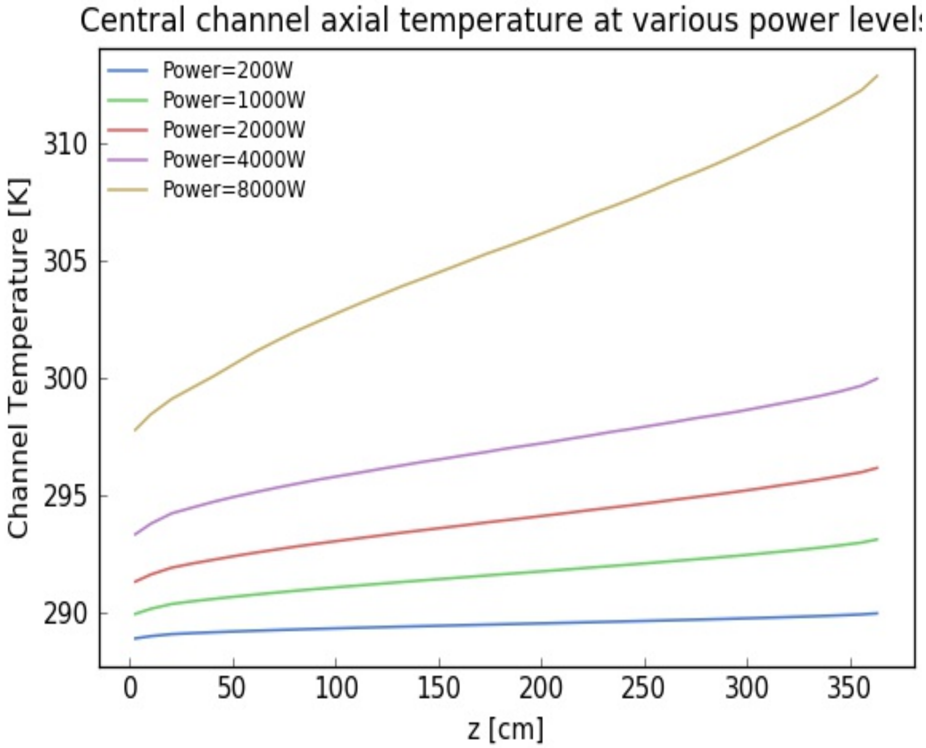


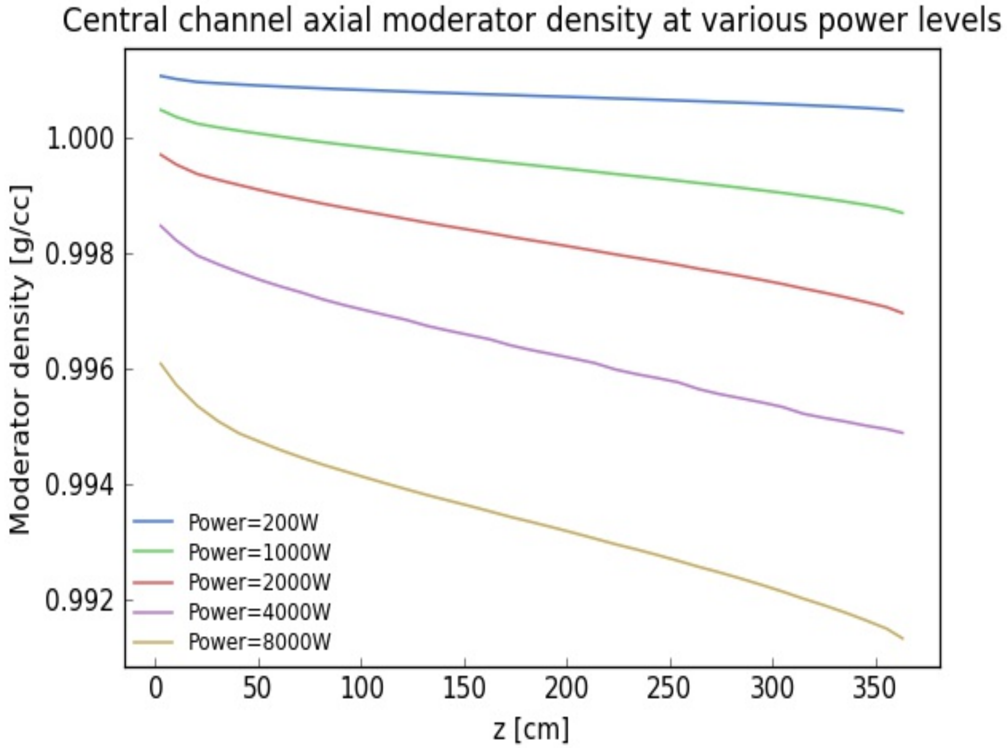
Test Problem (multiphysics coupling): 17x17 PWR assembly in stainless steel box

- 200W total system power
- Outer boundary fixed at 60 deg F (thermohydraulics)
- Reflecting boundaries (radiation transport)
- 18 axial levels
- $6x10^6$ active particles
- Converged in 3 iterations



Test Problem (multiphysics coupling): 17x17 PWR Assembly at various powers





As-Loaded analysis demonstrates subcritical margin for the majority of analyzed canisters

- As-loaded analysis shows margin to criticality for more than 60% of canisters analyzed under the disposal scenarios considered
- Flux trap designs show large margin under loss-of-absorber scenario
- Fewer egg crate canisters show margin
  - Improved damaged fuel assumptions may provide relief for some
- BWR as-loaded analysis capability should be extended to support modern multi-lattice fuel
  - Challenge: Need modern fuel and BWR reactor operational data
- As-loaded criticality analysis should be supported by depletion and criticality code bias and bias uncertainty analyses
- Demonstrated initial coupling in *Terrenus* between Monte Carlo radiation transport and subchannel thermal hydraulics codes